Shallow sediment structure and possible slope failure off the northern coast of Papua New Guinea

Takeshi Matsumoto[1], David R. Tappin[2], and SOS-4 Onboard Scientific Party

[1]***Japan Marine Science and Technology Center, Natsushima-cho, Yokosuka, Japan***
[2]***British Geological Survey, Keyworth, Nottingham, United Kingdom***

Abstract. The Sissano Offshore Survey (SOS) program started in 1998 in order to study the origin of the 1998 Papua New Guinea earthquake and the subsequent large-scale tsunami that occurred on 17 July 1998 on the northern coast of the Papua New Guinea mainland. Through the previous three research cruises under the program, the possible collapse, underwater landslide, and seismic faulting on the amphitheatre off Sissano Lagoon were identified successfully. The SOS-4 cruise was carried out in February 2001 to study the subsurface structures corresponding to the hazardous earthquake and tsunami events by use of a digital single-channel seismic profiler. Both the focused survey on the amphitheatre area to identify active deformational structures and the regional survey off Vanimo–Sissano–Aitape identified some recent/fossil events and regional tectonics. Contrast in the sedimentary layer features between the eastern and western half of the amphitheatre was observed clearly. The eastern half is characterized by layered stiff sediment where a rotational failure should have taken place after the 1998 earthquake. Relics of sliding of soft sediment were observed on the slope of the western half of the amphitheatre. A 70 km^3 block of a transparent sedimentary layer, apparently derived from a slope failure, was located in the fore-arc area of the New Guinea Trench off Vanimo. The sediment block completely fills the fore-arc basin. The whole area is characterized by an oblique subduction of the Caroline Plate toward WSW and the tensile stress perpendicular to the strike of the trench, considering a number of normal faults located in the study area.

1. Introduction

The northern coast of Papua New Guinea is characterized by a plate convergent margin along the Wewak Trench and the New Guinea Trench (Cooper and Taylor, 1987), with subduction of the North Bismarck Sea Plate underneath mainland Papua New Guinea on the Australian Plate (Tregoning *et al.*, 1998). Sissano Lagoon and the Town of Aitape, located in Sandaun Province, northern coast of Papua New Guinea, suffered enormously from a M 7.1 earthquake which occurred at 08:49 (UTC), 17 July 1998 (Ripper *et al.*, 1999). A large-scale tsunami was observed just after the earthquake and more than 2200 people were killed due to the run-up of the tsunami in the Aitape and Sissano areas.

The SOS (Sissano Offshore Survey) program started through the request from SOPAC to JAMSTEC after the 1998 earthquake and tsunami. The main objectives of the project are: (1) to detect the nature of the "1998 Papua New Guinea Tsunami," (2) to detect the seismic fault, possible underwater landslide and the mechanisms of tsunami occurrence, and (3) to detect the process that took place in the epicentral area and their driving forces of these phenomena and regional tectonics.

[1]Japan Marine Science and Technology Center, 2-15 Natsushima-cho, Yokosuka 237-0061 Japan (matsumoto@jamstec.go.jp)

[2]British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, United Kingdom (d.tappin@bgs.ac.uk)

In January 1999, a regional bathymetric and geophysical survey was carried out by R/V *Kairei* as a SOS-1 cruise (cruise ID KR98-13). Based on the results from the cruise, precise visual observation and sampling were carried out by R/V *Natsushima* and ROV *Dolphin-3K* in February (SOS-2 cruise, cruise ID NT99-02) and by R/V *Natsushima* and Research Submersible *Shinkai2000* (SOS-3 cruise, cruise ID NT99-15). Remarkable tension cracks extending up to 15 km were observed along the mid-slope of the amphitheatre through the dive surveys in SOS-2 and SOS-3 cruises (Tappin *et al.*, 2001), which apparently corresponds to the upper part of an underwater landslide along the amphitheatre and derived from the tensional stress of the mass wasting. The contrast between the eastern and western part of the crack was also described and it was concluded that it is to be derived from the nature of the sediment. The sediment in the eastern part of the amphitheatre is cohesive due to a certain process of compaction or some specificity of the origin of the sediment derived from the nearest on-land area. Then the possible collapse, underwater landslide, and seismic faulting on the amphitheatre off Sissano Lagoon were identified through these three cruises.

Detailed topographic features off the northern coast of Papua New Guinea were identified through the swath bathymetric survey by the SOS-1 cruise. Finally, the survey box was 3°20′S $\sim$ 2°00′S, 141°00′E $\sim$ 143°30′E. The area of 19,000 km^2 was almost fully covered by the swath survey of the SeaBeam2112 system.

The amphitheatre NNE of Sissano Lagoon is associated with an ENE–WSW-trending knoll just off the basin (Pop-up Block (PUB)). The western half of the amphitheatre is characterized by erosion by small channels perpendicular to the topographic contour line, while the eastern half is characterized by sediment deposition lobe parallel to the strike of the steep slope. There is a topographic high with a subsided coral reef south of the amphitheatre. Since the water depth of the subsided reef is about 460 m, there should have been a regional deformation in this area by more than 400 m. This amphitheatre seems to be most active and with most recent seafloor deformation according to the topographic feature.

The M 7.1 main shock was at first assumed to be due to "the 40 km fault" which is an E–W trending fault scarp the length of which is about 40 km located 25 km north of Sissano Lagoon. The topographic lineament of the fault scarp is elongated from the eastern edge of the amphitheatre at 142°E up to the trench axis at 142°27′E. The lineament, however, seems to be split into two by PUB and no sign of the overriding of the fault scarp is observed on the PUB. Therefore, the main shock does not correspond to the fault on the seafloor. The origin of the tsunami should be another fault or some other seafloor deformation.

The New Guinea Trench is located about 50 km north of the coastline. The general trend of the trench is N45°W. However, the landward side of the trench is characterized by topographic lineations of EW escarpment and the other parallel to sub-parallel to the general trend of the trench axis. The eastern end of the trench with a water depth of about 3000 m is located about 40 km NE of Aitape. Toward the NW, the width and water depth of the trench increase gradually. Maximum water depth in the study area is 4200 m about 50 km NNE of Sissano Lagoon. Several seamounts of the ocean floor are colliding against the trench on the northern side from the North Bismarck Sea Plate.

The study area is also characterized by development of deep sea canyons, channels, and topographic depressions. Small-scale straight valleys apparently due to the erosion on the shelf slope shallower than 1000 m are predominant. The most remarkable is the meandering channel north of the Yalingi River west of Aitape, located in the amphitheatre 25 km off the coast between Aitape and Sissano Lagoon. These topographic depressions may play the important role of a propagator of tsunamis when a certain seafloor deformation takes place nearby.

2. The SOS-4 Cruise

A precise shallow seismic profiling image is essential to locate the earthquake faulting and/or slope failures, their size, and distribution, which identifies the tsunamigenic potential. The SOS-4 cruise (cruise ID NT01-01) was planned to study the sub-surface structures corresponding to the hazardous earthquake and tsunami events in 1998. Therefore, surveying sub-bottom structure by use of digital single-channel seismic profiling was exclusively carried out during the whole cruise. Primarily, the information obtained from the cruise was of great help for geological mapping of the amphitheatre area where an active deformational structure caused by underwater landslides and/or earthquake faulting were revealed by the previous cruises. Secondarily, a regional survey off Vanimo–Sissano–Aitape was also carried out in order to identify regional tectonics which is to be a background of the present events. Detecting fossil events was also planned to measure the rate and frequency of the geohazardous phenomena in the study area. Characterization and volume estimation of the slump sediment along the amphitheatre offshore Sissano Lagoon was mostly prioritized for this cruise. Therefore, the first 4 days was focused on the surveying of the amphitheatre, PUB, and nearby in order to get pseudo 3-D images of the sub-surface structure by closely spaced survey lines with a spacing of 0.5 nm. Then a regional survey was started to cover the pre-surveyed area by a SOS-1 cruise. The other purpose of the seismic profiling is to acquire more field data in order to improve the reliability of the numerical simulation of the propagation of the tsunami. The data will also be used to assess the fossil and future tsunami hazards through the simulation procedure (Fig. 1).

Lines #1–32 were mainly for the amphitheatre study with 25 short NS lines with the spacing of 0.5 min of arc and 7 ENE–WSW trending tie lines (Fig. 2). These lines covered between the submerged delta slope off the Sissano Lagoon in the south and "the 40-km fault" in the north, and from the Yalingi Canyon in the east to the central region of the subsided delta in the west. The amphitheatre and the PUB were completely mapped through the survey.

Line #33 was a crosscheck line of the profiling of the NNE–SSW transects

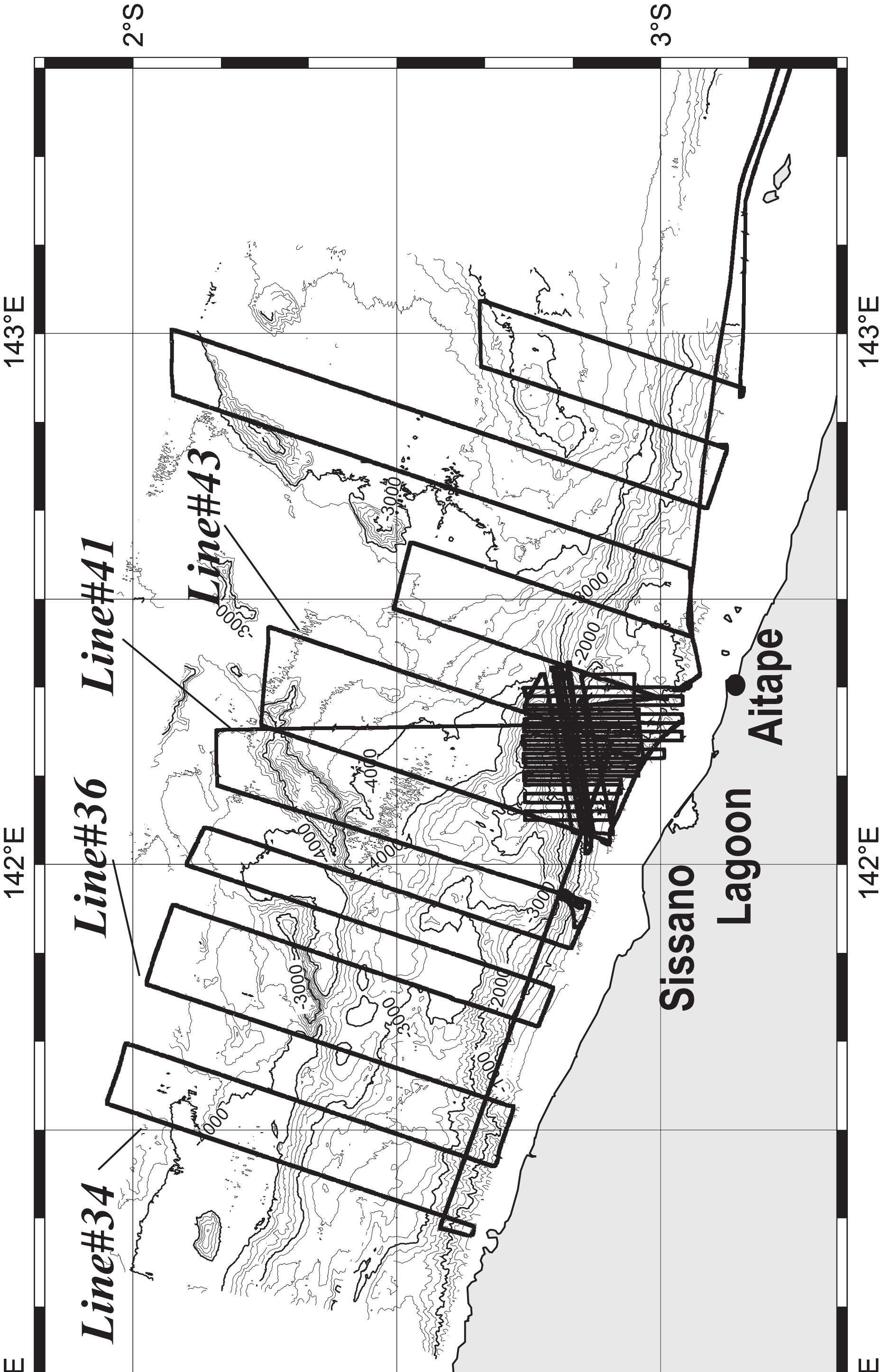

Figure 1: All survey track lines of the SOS-4 cruise. Survey line numbers on the figure are referred to in Fig. 4.

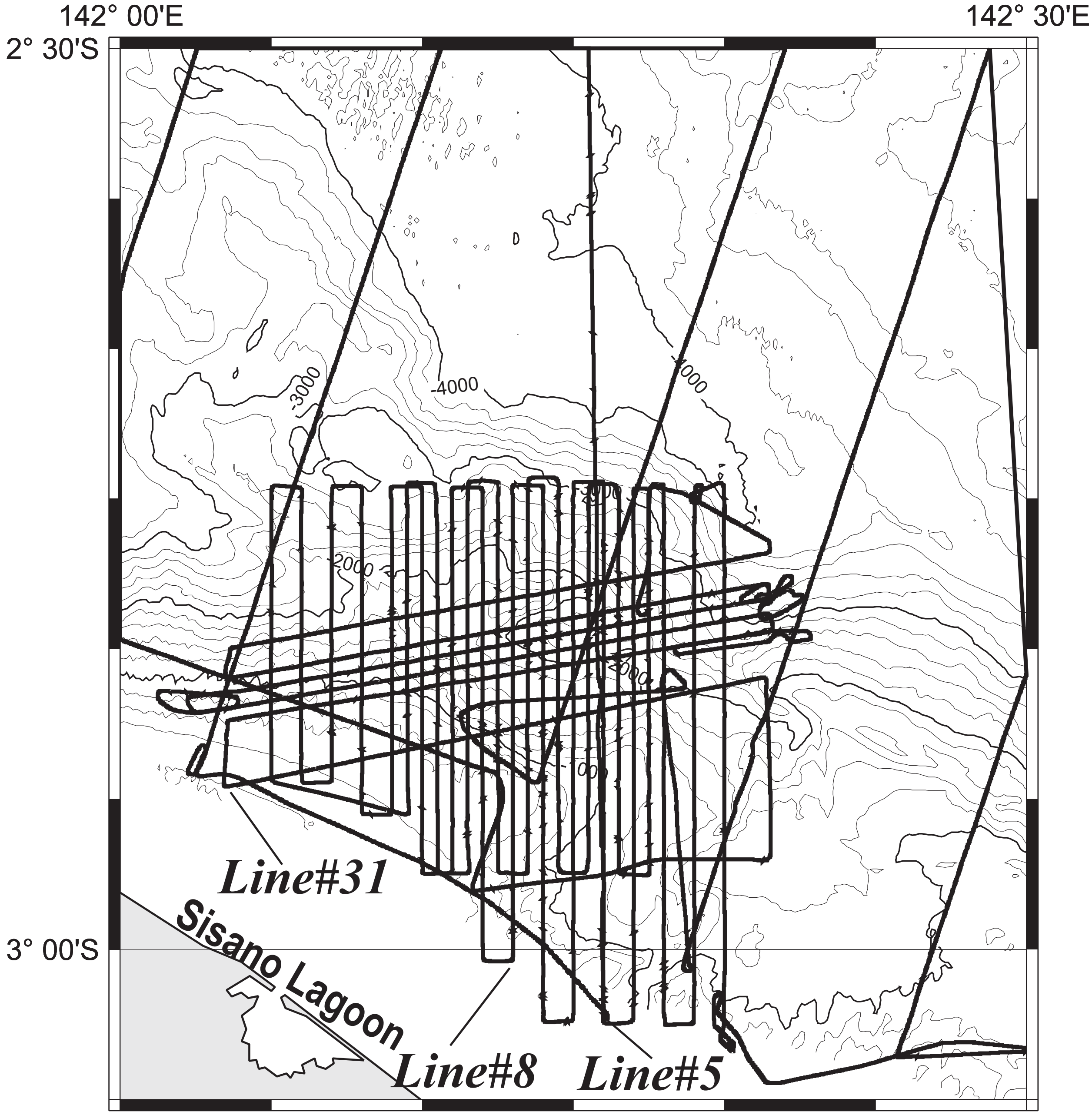

Figure 2: Survey track lines in the amphitheatre area. Survey line numbers on the figure are referred to in Fig. 3.

and was planned to transit from the amphitheatre to the westernmost line off Vanimo. Lines #34–49 were for a regional survey along the transects completely crossing the New Guinea Trench in the western half and crossing the Wewak Trench and the western part of the Bismarck Sea in the eastern half. Line #41 followed the previous multichannnel profiling line (Sweet and Silver, in press) for the reference of the interpretation of the new seismic profiling records.

3. Results

3.1 Amphitheatre area

The representative seismic profiles crossing the eastern and western part of the amphitheatre and also crossing the slump sediment on the foot of the amphitheatre are shown in Fig. 3.

Line #5 confirms that the type of the slump in the eastern part of the amphitheatre from the upper scarp to the foot of the mound is a rotational failure of cohesive sediment layer with little disturbance on the surface. However, Line #8 shows that quite a different feature of the slumping is taking place in the western part of the amphitheatre. The headwall is characterized by a short-wavelength topographic undulations on the slope apparently derived from a number of surface sediment slumps. The foot of the slope is a layered rather transparent sediment block suggesting that the block has been formed by several surface failures of the headwall. The additional cross line (Line #31) also shows the contrast between the western and eastern part of the amphitheatre and suggests that the pattern of the failure is complex. The horizontal size of the slump was estimated as 5 km (E–W) times 4 km (N–S). The slump margins are sharp with a maximum thickness of 600 m, tapering to the northern and southern margins.

"The 40-km fault" located 30 km off the Sissano Lagoon was clearly identified on the seismic record and is interpreted to be a normal fault down-dipping toward the north, as suggested from the multibeam bathymetric survey in the SOS-1 cruise. "The 14-km fault" on the southern slope of the PUB was also identified and is interpreted to have a predominant normal component of down-dipping toward the south.

3.2 Regional structure

The representative seismic profiles of the regional seismic survey crossing the New Guinea Trench are shown in Fig. 4.

Line #34 is planned to get a "typical" slope basin–trench slope–trench floor profile. The slope basin is filled with soft sediment of 0.6 s TWTT with a disconformity inside it. The ridge between the slope basin and trench floor is made up of a stuff sediment on the basement—perhaps consisting of sedimentary rocks. The location of the trench axis is not clear because the topographic feature of the trench floor is flat and the width of the trench floor is some 20 km. The water depth is 5.65 s TWTT on the southern side and 5.45 s TWTT on the northern side with a step associated with a

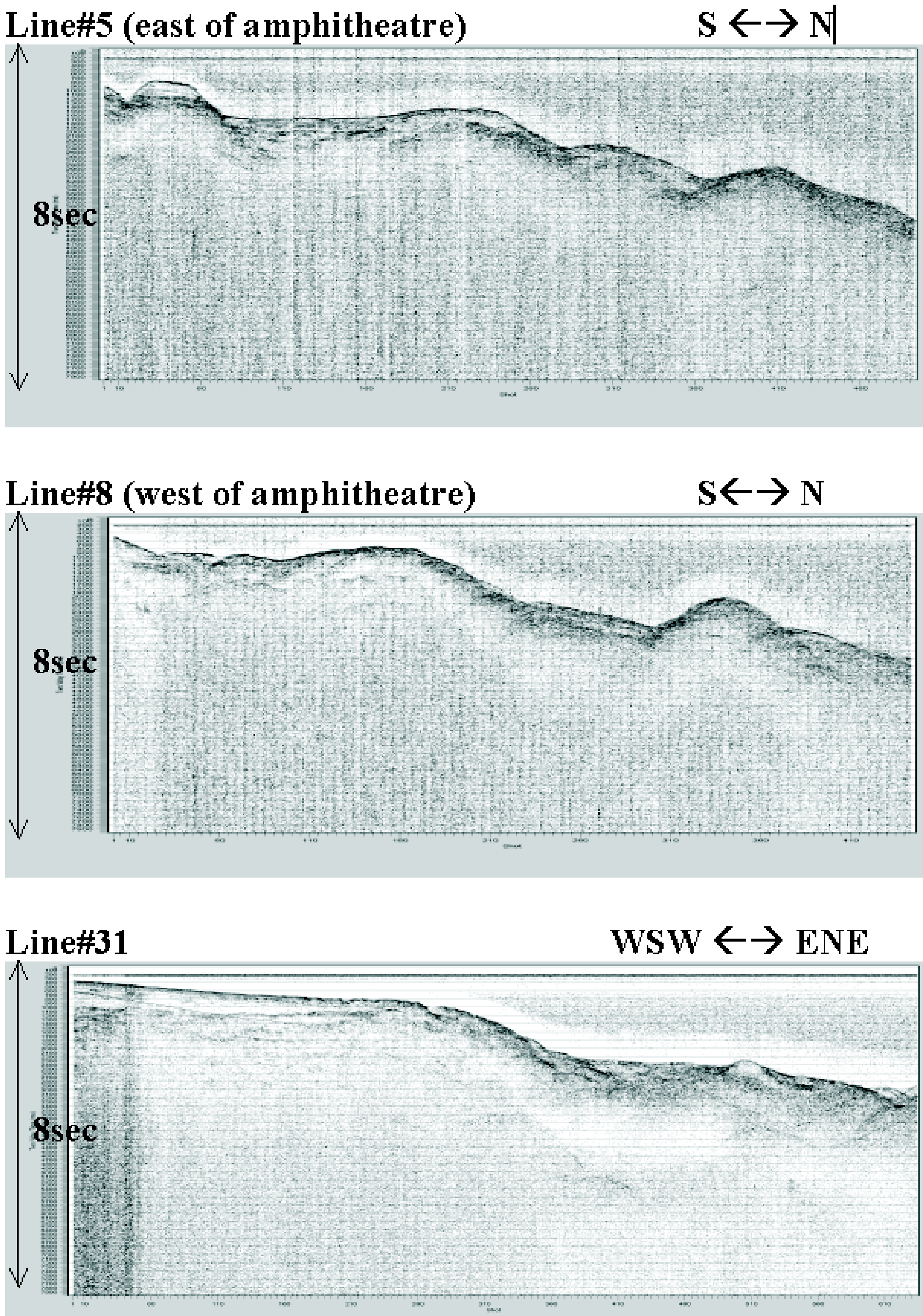

Figure 3: Some examples of the single channel seismic profiling in the amphitheatre area.

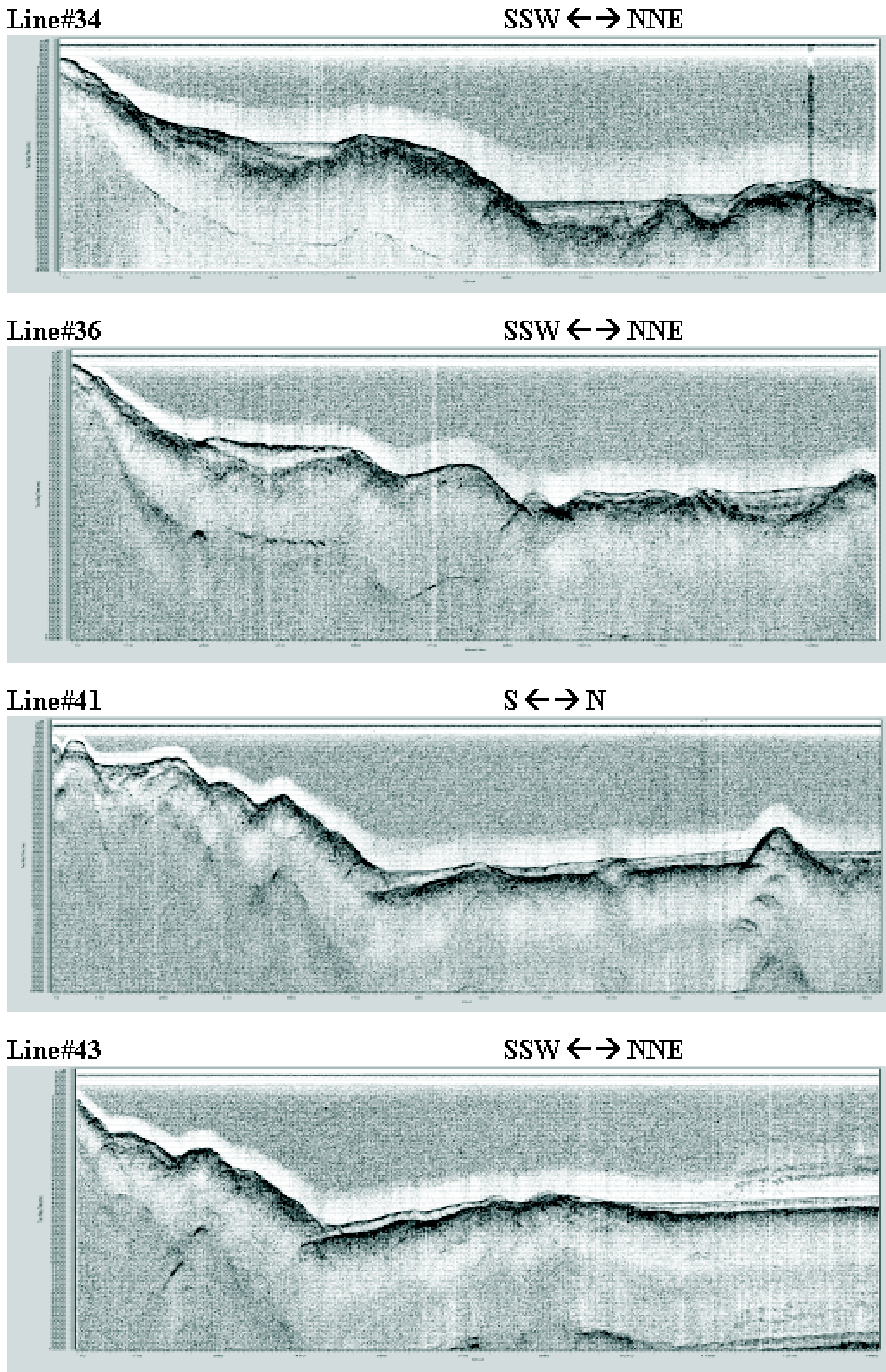

Figure 4: Some examples of the regional single channel seismic profiling across the New Guinea Trench off the northern coast of Papua New Guinea.

seamount apparently subducting toward the trench and covered completely with abyssal sediment. Another seamount also subducting toward the trench is located at the end of the profile.

Relics of a remarkable underwater landslide were observed along Line #36. The surface of the slope just beneath the shelf is characterized by a sliding with rough undulations and a block of a transparent sedimentary layer is located on the extension of the slope basin. Maximum thickness of the sediment block is some 0.9 s TWTT. The block corresponds to the topographic high with surface undulations off the canyon. Considering that the area of the topographic high is 14 km times 14 km, the total volume of the slump sediment block is some 70 km^3. However, it should be noted that at least three different layers are observed inside the block by the processed record; it is not always concluded that the whole block slid at one time, but at least a couple of events of underwater landslide on the slope nearby constructed the slump sediment block. One part of the sediment flows to the downslope toward the ridge facing the trench axis. A subducting seamount massif also exists on the trench floor.

Line #41 is following Line #1a and Line #1b of the previous multichannel survey (Sweet and Silver, 2001), crossing the amphitheatre from far north. The end point is the Yalingi Canyon eroding the fan sediment. The location of the trench axis is clear from the depth profile. It is clear that the basement of the foot of a sunken seamount is subducting underneath the foot of the PUB.

Line #43 crosses the amphitheatre headwall, sediment mound, PUB, trench axis, and the western edge of a volcanic massif on the North Bismarck Sea Plate. The summit is not covered with sediment but cut toward the trench axis by a fault scarp which is apparently a normal fault. The slope of the volcanic massif is covered with sediment of maximum 0.3 s TWTT. On the slope toward the trench axis three other southward dipping normal faults cut the sedimentary layer and volcanic basement rock. The foot of the massif is apparently subducting underneath the trench slope. The northern slope is also cut by four northward dipping normal faults, suggesting that the area is characterized by predominant N–S tensional stress which causes normal faults and active slope failure.

4. Discussion

A remarkable en echelon tension crack, corresponding to the tensional stress on the upper part of an underwater, was observed along the mid-slope of the amphitheatre through the dive surveys in SOS-2 and SOS-3 cruises. The crack extends up to 15 km. Observation from these two submersible cruises also showed that fresh tension cracks with a sharp edge in the eastern to central part and those with a round edge covered with sediment in the western part, suggesting that this part is rather old. The contrast between the eastern and western part of the crack is also described by the small-scale topographic features (Tappin *et al.*, 2001). This is also supported by the result of piston core samples showing no sign of recent turbidity current on the foot of the amphitheatre. Seismic data confirms that sediment slumping has taken place on the amphitheatre and also confirms the contrast between both sides. A clear northward dipping lower reflector on the foot of the western part of the amphitheatre scarp is interpreted as a fossil fault escarpment over which 300 m-thick (0.4 s TWTT) soft slump sediment overrode. The lower reflector underneath the amphitheatre scarp and the slump sediment mound north of the scarp is interpreted as a formation of the rotational failure underneath the slope. The failure of the upper scarp identified during the previous SOS surveys is considered to be the most recent failure event.

Both "the 40-km fault" and "the 14-km fault" on both sides appear to be normal. However neither of them appears to be a likely source of the 1998 tsunami, as has been concluded from bathymetric and seafloor image data (Tappin *et al.*, 2001).

The whole area is characterized by an oblique subduction of the Caroline Plate from ENE to SWS (Weissel and Anderson, 1987; Tregoning *et al.*, 1998). In this case, relative motion between the two plates is not perpendicular to the strike of the trench. If the lithospheric thickness differs from each other (in most cases the lithosphere of the oceanic plate is thicker than that of the continental plate), thicker lithosphere sinks down due to its weight and thinner lithosphere moves toward the thicker lithosphere like a density current. Then the convergent plate boundary (trench) shifts toward the seaward side and rolling back of the oceanic lithosphere takes place. The surface of the convergent plate boundary area is characterized by tensile stress. Slumping of the surface sediment and normal faults appear remarkably in this case. The findings obtained during the cruise in the study area are described by the simple density current model.

Many seamounts subducting underneath the trench slope are observed in the present study area. If the size of the seamount is smaller than several kilometers, the seamount load is supported by the restoring force of elastic bending of the oceanic crust. However, the load of seamounts or oceanic plateaus the horizontal size of which exceeds 100 km is hard to be supported by elasticity and is supported by buoyancy by thick crusts underneath them. Small seamounts subduct easily if they reach the trench axis and the restoring force that supported them disappears. However, large-scale seamounts supported by buoyancy never subduct at the trench axis because they are stable mechanically. In this case, the seamounts are included into the continental plate and the convergent boundary (trench axis) jumps to the seaward side of the seamounts because the lab-pull force is still effective in the collision.

5. References

Cooper, P., and B. Taylor (1987): Seismotectonics of New Guinea: A model of arc-reversal following arc-continent collision. *Tectonics, 6*, 53–67.

McSaveny, M.J., J.R. Goff, D.J. Darby, P. Goldsmith, A. Barnett, S. Elliot, and M. Nongkas (2000): The 17 July 1998 tsunami, Papua New Guinea: Evidence and initial interpretation. *Mar. Geol., 170*, 81–92.

Ripper, I.D. and H. Letz (1999): The Sissano Lagoon (Aitape) tsunami: Which earthquake was responsible? *Papua New Guinea Geological Survey Report 99/7.*

Sweet, S., and E.A. Silver (in press): Seismic reflection images of the source region of the 1998 Papua New Guinea tsunami. In *Prediction of Underwater Slide and Slump Hazards*, edited by P. Watts, C. Synolakis, and J.-P. Bardet, Balkema, Rotterdam, Netherlands.

Tappin, D.R., P. Watts, G. McMurtry, Y. Lafoy, and T. Matsumoto (2001): The Sissano, Papua New Guinea tsunami of July 1998—Offshore evidence on the source. *Mar. Geol.*

Tregoning, P., K. Lambeck, A. Stolz, P. Morgan, S.C. McCluskey, P. van der Beek, H. McQueen, R.R. Jackson, R.P. Little, A. Laing, and B. Murphy (2000): Estimation of current plate motions in Papua New Guinea from Global Positioning System observations. *J. Geophys. Res., 103*, 12,181–12,203.

Weissel, J.K., and R.N. Anderson (1978): Is there a Caroline plate? *Earth Planet. Sci. Lett., 41*, 143–158.